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PHYSICS OF THE MOON

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Goddard Space Flight Center
National Aeronautics and Space Administration

PHYSICS OF THE MOON

The moon was probably formed four and a half billion years ago and was captured by the earth shortly after its formation. It is a body whose surface has preserved the record of its history remarkably well. The lunar surface is covered with a lacework of craters, believed to have been produced by the impact of meteorites. These meteorites have presumably been colliding with it during all the period since its capture, and the trace of their impact on the moon is perhaps the only physical record which we have of properties in the development of the solar system going back to that early time.

It is a remarkable fact that all of the craters on the moon, without exception, are almost exactly circular. See Figure (1). On the earth if we were to stake out a circle on the surface and come back after a billion years, we would find that it had been pushed and pulled out of all recognition by displacements and upheavals which distort the surface markings of the earth in times of the order of ten million years. The surface markings of the crater would often be destroyed by wind and water in a time of approximately

the same magnitude. On the moon there is no erosion by atmosphere, and in fact there are no mechanisms for appreciable erosion of any kind. At the same time, the circularity of the craters on the moon shows that there has been little, if any, tectonic activity; apparently the moon is a cold and lifeless body in the geological sense. For these reasons -- the absence of erosion and tectonic activity -- the surface of the moon has preserved the record of its history extending back through many billions of years to the earliest period of its infancy and to the beginning of the solar system.

Moreover, by virtue of this same antiquity of its surface, the moon holds another remarkable record layer of cosmic dust which has presumably rained on it from the solar system and from outside the solar system since its formation. This dust may be as much as a foot or more in depth, and in it we may find organic molecules and the precursors of life on earth which will provide clues to the origin of physical life.

Thus, we see that the moon may hold clues to the origin and history of the solar system, and to the origin of physical life. These clues have been lost on earth by the combination of erosive forces and tectonic activity.

Presumably this record has been lost on Venus, which is a planet quite similar to the earth, and it has probably also been

lost on Mars; this is a planet which is substantially smaller than the earth and therefore may resemble the moon and its properties, but yet it is large enough so that in an earlier stage in its history there were doubtlessly extensive oceans and atmosphere covering its surface.

For this reason the moon is an object of exceptional interest to the physicists, more so in fact than either Mars or Venus. It is the only accessible major object in the solar system on which the record of the solar system may be preserved.

The foregoing point of view regarding the unique importance of the moon has been emphasized by Harold C. Urey in the last ten years, and his research has been largely responsible for the revival of interest in the moon among physicists and astronomers.

In the most recent work of Urey, and even more so in the investigations of Gordon J. F. MacDonald carried out over the last two years, attention has been drawn to interesting properties which the moon may have as a planetary body, e.g., its composition, internal density variations, and thermal history. In the continuing study of the moon these features do begin in fact to assume a greater importance than the superficial characteristics which first strike the attention of the lunar observer.

I. PROPERTIES OF THE MOON AS A PLANETARY BODY

The orbit of the moon is inclined at an angle approximately

five degrees to ecliptic; its mean radius is approximately 400,000 kilometers; the period of revolution is 27.3 days; its orbital eccentricity is 0.055; its radius is 1700 kilometers or approximately 1/4 of the radius of the earth; its mass is 1/80 the mass of the earth.

The mean density of the moon is 3.34, and this is the only bulk physical datum regarding the moon which is at present available. The moon's density is close to that of a common type of meteorite known as the chondrite, which is another sample of extraterrestrial matter. The chondrites form the two groups of different iron contents, with respective densities of 3.51 and 3.66. The density of the moon should not be exactly that of the chondrites, since conditions of pressure and temperature in the moon's interior will result in some effect on density. However, it is tempting to speculate that the moon is in fact made of the same material as the chondritic meteorites, and that their origins and histories are connected in some way. The chondritic meteorites are believed by most observers to come from the asteroidal belt, and it is possible that the moon is simply a meteoritic fragment of exceptional size which was captured by the earth.

The Figure of the Moon

The moon's figure resembles that of the earth in that it is larger at the equator than at the poles. Its equatorial

bulge may be understood as a result of centrifugal forces produced by the rotation of the moon about its own axis.

In addition, the moon has a nose pointing toward the earth, which has presumably been pulled out like taffy by the gravitational attraction of our planet.

Both the equatorial bulge and the nose can be calculated from the present period and radius of the lunar orbit, if we assume that the moon's interior is plastic. ~~and~~ The result of our calculations is a difference of polar equatorial radii equal to some tens of meters, and a nose whose height is again some tens of meters.

The observations on the figure of the moon, though not precise, suggest that the equatorial bulge and the moon nose actually have magnitudes of approximately one kilometer. Thus, the moon has a highly distorted figure, greatly different from that which we expect on the assumption of a plastic interior, and this is an extremely significant result. Calculations indicate that the present distortions are in fact those we would expect at an earlier stage in the moon's history, when it was closer to the earth, perhaps 100,000 kilometers away, and both the speed of rotation and the tidal forces were substantially greater.

Apparently the moon has preserved in frozen form the distorted figure of its infancy because it is at too low an internal temperature to provide the plasticity which would adjust to changing conditions.

There are other indications that the moon is a relatively cold body, such as the apparent absence ~~of~~ or scarcity of volcanoes and tectonic activity, ~~and lunar volcanoes~~, but the distorted figure of the moon is perhaps the strongest argument for a low internal temperature.

Gordon MacDonald of UCLA has carried out extensive calculations on the thermal history of the moon, on the assumption that it has a chondritic composition with the relative percentages of the naturally radioactive elements found in the chondrites. MacDonald finds that if the temperature of the moon were 600° or higher, the internal heating produced by the decay of radioactive elements would raise its temperature to a level at which extensive melting must be expected. The figure of the moon implies that it has never been at a sufficiently high temperature for extensive melting to occur, since the earlier stages of its history, and MacDonald's calculations therefore suggest that the moon must have been initially at a very low temperature. That is, the primitive moon was a cold moon.

Start B here

Life as we know it on
earth is excluded on the
surface of the moon
by ~~the~~ measurements
of the temperatures reached
at the lunar
mid-day.

MacDonald's result is of considerable interest because it has a bearing on theories of the origin of the solar system. If the solar system was produced in the chance collision of two stars, we expect that initially the bodies of planetary size would have condensed out of masses of hot gas and that therefore these primitive bodies would have been at a very high temperature. If, on the other hand, the solar system condensed out of fluctuations in the process of gravitational contraction from which our star was born, as is now the favored theory, we may expect that the moon and the planets were initially at a very low temperature. MacDonald's calculations and the evidence on the figure of the moon support the theories of a cold primitive moon.

II. SURFACE ~~OF THE~~ MOON

We now turn to the surface characteristics of the moon. These have some bearing on the fundamental problems of lunar origin and history, and they are also important for the preliminary design of lunar exploration vehicles.

~~Temperature~~

B

The temp. of the lunar surface has been ~~meas.~~ determined by placing a detector sensitive to heat radiation at the focus of

~~Measurements at~~ the 100-inch telescope on Mt. Wilson ~~with~~

The Mt. Wilson measurements show that

a ~~vacuum thermocouple~~ show the temperature of the moon ~~to be~~

rises from a low of -180°C at night to a peak of 130°C

~~approximately 400° Kelvin or 130° Centigrade at full moon~~ during

~~the lunar midday~~ when the sun is overhead. Bacteria have

the ~~subsolar point.~~ ~~At night, the temperature falls to approxi-~~

been found in hot springs at 90°C, but it is believed that

~~mately 120° Kelvin or -150° Centigrade.~~ ~~These measurements~~

the macromolecules which constitute the basis of all chemistry ~~will be~~ cannot remain intact at temperatures higher than that.

B

represent very great temperature extremes. In particular, the temperature at full moon is higher than believed to be possible for the existence of life as we know it on earth. The temp. below the surface has also been measured by observing the intensity of radio waves emitted from the lunar disc. These waves — margin next page.

In an eclipse the temperature variation at one point on the moon near the limb was measured by Pettit. The measurements of Pettit indicated that the change from a value near the daytime maximum to a value near the nighttime minimum occurred in approximately one hour as the eclipse progressed.

Dust or sand, in the vacuum which we know to exist on the moon, would have a very low conductivity, such as the measurements of Pettit suggest.

A closer analysis of the Pettit cooling curve, carried out by Jaeger and Harper in 1952, shows that this curve cannot be explained by any theoretical analysis based on a single layer of arbitrary conductivity. Rather it requires two layers, and Jaeger and Harper have shown that these must be a thin layer of some substance such as dust, approximately two millimeters in thickness, on top of a porous substance such as sand or fine gravel. The results of Jaeger and Harper dictate our impressions of the characteristics of the lunar surface at the present time.

Subsurface Temperature

Piddington and Minett have observed the intensity of the 2400 megacycle radiation from the lunar disk, which measures

These waves come not from the surface but from a depth of a foot or two below. ~~Their~~ ~~intensity~~ ~~is~~ ~~proportional~~ to

~~the temperature below the surface. The temperature of this~~ these waves is proportional to the temperature radiation represents conditions one optical thickness beneath the surface at that frequency, and we may estimate that an optical thickness is of the order of some inches or a foot in the region of 2400 megacycles. Piddington and Minett find for the subsurface temperature, measured in this way, a value of 234° Kelvin or -39° Centigrade. This result represents a much more comfortable condition than the extremes of day and night determined on the surface proper. It is interesting to note that the subsurface temperature is approximately the average of the day and night temperatures recorded above.

The temp ~~at that~~ ~~depth~~ ~~and~~ reveals that the ~~subsfa~~ temp. at that depth is cool but relatively comfortable -40°C

Surface Smoothness

The best lunar photographs are taken near the terminator, where the sun is low and long shadows bring out the relief of surface features. As a result, the impression has been generated that the moon consists of craggy peaks and ramparts rising precipitously from a flat crater floor. An artist's sketch of this conception of the moon's surface is shown in Figure (2).

Actual measurements of the slopes, obtained by the observation of shadow length during the course of the lunar day, have shown that this conception of the surface is false. Figure (3) shows an elevation profile representing a cross-section through the center of Theophilus, a crater in the southwest sector of

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the moon. A photograph of Theophilus is also shown, obtained near the terminator and suggesting a very rugged terrain. The elevation profile indicates that Theophilus consists of a 15,000-foot rampart and a 7,500-foot central peak, the latter buttressed by three subsidiary peaks.

In spite of the formidable appearance of Theophilus the measured elevation profile shows the slopes to be actually quite gentle, no more than 6° on the average throughout the cross-section of the equator. With the elevation profile and the photograph as a guide (Figure 3), we have developed our own artist's conception of the appearance of Theophilus as it will appear to two observers standing on the left, the first human observers to land in that region (Figure 4). The landscape seems to be a gentle rolling terrain, in which the ramparts appear barely visible on the horizon and the central massif is quite an unimpressive elevation. The actual terrain is even more monotonous, because the elevation profile and the drawing in Figure (4) were constructed on a flat base, and actually the moon's surface curvature would bring the crater rampart below the horizon so that it could not be seen at all. In general, we can say that the terrain of the surface of the moon resembles the Sahara Desert more closely than it does the rugged mountain ranges with which we are familiar on earth.

Smoothness in the Small

Not only is the lunar surface gentle in the large, but it also appears to be remarkably smooth in the small on the scale of a few inches. The evidence for this comes from radar reflections in the region of 10 centimeters of wave length. It is found that the reflected radar pulse has a very sharp peak which suggests that most of the reflection comes from the close vicinity of the sub-terrestrial point. That is, the moon reflects as a rather well polished sphere for electromagnetic waves in the region of 10 centimeters, although it is a diffuse reflector and therefore a rough surface for radiation in the optical region.

The smoothness of the moon on a scale of a few inches is surprising when we consider that the surface should be pitted by the hail of small meteorites raining down on a surface over many aeons. Apparently these pits have been filled in, perhaps by the dust which we believe exists on the surface. The question is, what transports the particles of dust around and fills in the holes? Perhaps The continued bombardment by ~~rain of~~ micrometeorites ~~may be~~ breaks down the surface ~~into particles of such small scale~~ and smooths out the irregularities. responsible for the transport, but Gold has come up with a different and more original suggestion -- that the bombardment of the surface by solar particles produces an occasional transfer of charge with the result that the electrostatic repulsion causes them to hop away from their original sites. Gold has

produced such conditions as this in the laboratory and it is possible that his explanation does provide the major transport mechanism. However, the question must be considered quite open for the present time.

The Origin of the Maria

Finally we come to perhaps the most puzzling of the major lunar surface features -- the great black seas or maria, which cover a large part of the moon. G. K. Gilbert, an American geologist, suggested in 1892 that these maria, and Mare Imbrium in particular, were lava flows produced by the melting of great meteorites on impact with the lunar surface. Fifty years later, H. C. Urey independently introduced the same theory. However, Gold, MacDonald, and Dietz have objected to this hypothesis on the grounds that most of the impact energy will go into the ejection of a vast cloud of dust and rock fragments, and little into melting. On the airless moon a substantial amount of the dust and rubble produced in the collision will fall back around impact center and form a relatively flat bed. In this view the maria are just such flat beds of dust and rubble.

On the other hand, Urey has pointed out that Mare Tranquilitatus, in the western sector of the moon, is hard to regard in any other way than as a lava flow. Figure (5) shows Tranquilitatus to have a darkened irregular outline resembling an ink blot.

It is possible that such a sea as Tranquility was produced by the welling up of lava from beneath the surface, and G. P. Kuiper

of Yerkes Observatory and Arizona University subscribes to that view. This may be the correct explanation, but it also has difficulties associated with it, namely, that the irregular figure of the moon indicates a cold body during most of its history, and a cold moon would seem to exclude the extensive melting which would be required to explain large lava flows on the surface.

In concluding our survey of lunar properties, we wish to commend that our present ideas regarding the moon's surface must be regarded as very questionable in the light of certain limitations. First, our lunar observers have a strong bias dictated by their knowledge of the surface of the earth, although, as we have indicated above, the histories of the terrestrial and the lunar surfaces probably have been completely distinct. Second, the resolution of surface features which can be seen from the surface of the earth in telescopic photographs is approximately one kilometer, and with so limited a resolution as this it is difficult to draw firm conclusions.

Each student of the moon's surface sees what he wants to see, and in fact very little has been learned about the moon in the last 60 years in spite of the great progress that has occurred in other fields of science. The truth is that we cannot learn more about the moon until we come closer to it and are able to undertake a direct physical exploration of the surface.

We are now about to embark on this rewarding phase of lunar investigation, and through it we hope to learn much of the origin

of the solar system and physical life. The program of lunar exploration may be expected to be among the most rewarding and exciting of all NASA projects during the next ten years because it involves the direct physical exploration of virgin territory, in the spirit of the voyages of exploration of the sixteenth and seventeenth centuries by which we came to know our own planet.

Of all the extraterrestrial bodies, the first to be explored will undoubtedly be the moon, which is the earth's nearest celestial neighbor. Mars and Venus are 100 times more distant, and a rocket that could reach the moon in a day or two would take months to arrive in the vicinity of one of these planets. An instrument station on the moon could also communicate with the earth more easily than one on Mars or Venus. The moon can serve as a way station <u>en route</u> to the planets, and as a testing ground for the development of the space craft and scientific instruments required for the exploration of the planets.

The lunar science program begins with the delivery of simple instrument packages to the vicinity and surface of the moon, a mission scheduled to take place during the next year or two, which will provide preliminary information on the surface structure, surface radioactivity, and level of seismic activity within the lunar interior. Later projects, some three to five years hence, will deposit more complex instruments on the

surface of the moon for TV reconnaissance of the nearby terrain and for detailed chemical and physical tests of the lunar matter near the landing site. Developments five to eight years in the future may involve the remote-controlled return of samples of lunar matter to the earth from the moon; and we may also be able to deposit unmanned remote-controlled mobile vehicles, capable of sampling the composition of the surface over a large area around the landing site.

The instruments for the initial lunar experiments will be carried to the moon on a spacecraft designated as the <u>Ranger</u> which is under development by the Jet Propulsion Laboratory of the California Institute of Technology. The Jet Propulsion Laboratory is operated for the National Aeronautics and Space Administration under a contract to the California Institute of Technology. It has been assigned the responsibility by the NASA for the present implementation of our unmanned lunar and planetary programs.

The <u>Ranger</u> spacecraft is shown in Figure (6). It contains the seismometer, detectors for measuring the level of radioactivity in the moon's surface, and TV systems designed to transmit back to the earth a succession of images of the moon as the spacecraft approaches the surface. The last of the TV images will be taken at a height of about 10 to 20 miles above

the lunar surface; it will cover a small area with a fine degree of resolution that will, if the system functions properly, provide details of surface structure about one hundred times smaller than those we can see in photographs of the moon taken by the best earth telescopes.

The seismometer will be detached from the main body of the spacecraft at some distance from the moon, and slowed down by the firing of a retrorocket as it approaches the surface, so that it can land with a sufficiently moderate jolt to permit it to function after impact. This impact is known as a _rough landing_; it may occur at a speed of as much as several hundred miles an hour, producing a force comparable to that of an airplane crashing into the side of a mountain, but the seismometer will be packaged to survive a crash of this magnitude.

Figure (7) shows the sequence of actions planned during the approach of the _Ranger_ to the surface of the moon.

Attached to the _Ranger_ seismometer will be a radio beacon which will transmit back to earth, if the instrument functions as planned, the data received by the seismometer on the level of earthquake or "moonquake" activity. The analysis of seismometer records on earth has given us most of our information regarding the internal structure of our planet, and it is hoped that this same instrument will furnish basic data on the internal structure of the moon.

The winglike structures shown in Figures (6) and (7) are panels containing thousands of solar cells, which will convert sunlight into electric power for the instruments and radio transmitters on board the spacecraft. Also shown mounted on the spacecraft is a directional antenna designed to transmit back to earth the information obtained by the TV systems and other instruments.

In Figure (8) the prototype of the *Ranger* spacecraft is shown under construction in the shops of the Jet Propulsion Laboratory in Pasadena, California. The rough landing capsule is being developed by the Aeroneutronics Division of the Ford Motor Company. Figure (9) shows the 85-foot directional antenna in Goldstone, California, which will be used by the Jet Propulsion Laboratory in tracking of the *Ranger* spacecraft.

Later projects in the lunar program will deposit more complex instruments on the surface of the moon for detailed television examination of the nearby terrain, and for chemical and physical tests of the lunar rocks and dust near the landing site. The spacecraft being developed for these projects is called the *Surveyor*. The *Surveyor* will have advanced guidance and control systems designed to deposit it gently on the moon's surface, at an impact speed of 20 miles an hour or less, in what is known as a *soft landing*. The *Surveyor* is under construction for the Jet Propulsion Laboratory by the Hughes Aircraft Corporation.

Engineering study programs also have been undertaken with a view to developing a remote-controlled drill, that will extract samples of subsurface lunar material for analysis by the instruments mounted within the body of the soft-landing spacecraft. A sketch of a design for a spacecraft in the <u>Surveyor</u> class is shown in Figure (10).

A project under investigation for possible future development involves the remote-controlled extraction of samples of lunar material, and the return of these samples to the earth in small unmanned rockets for analysis in our laboratories. We are also looking into the development of an unmanned mobile vehicle, which would navigate across the lunar terrain under the remote control of an operator on earth. This vehicle would be able to sample and analyze the composition of the lunar surface over a large area around the landing site. It would indicate the variations from point to point on the surface, and answer the important question whether the conditions measured at the site of the fixed stations represent the average conditions on the moon. A possible structure for this unmanned mobile vehicle is shown in Figure (11).

These projects will probably carry us through the decade of the 1960's, which represents the period of unmanned investigation by remote-controlled apparatus. Automatic instrumentation can be developed to a high degree of refinement, but Man

is a sensory device of extraordinary sophistication, with a marvelous ability to suppress irrelevant detail and detect the previously unexpected and unknown phenomena that are always our most important source of new information. Late in this decade, or early in the next decade, we expect to begin piloted lunar flights, in which we will extend Man's experience for the first time to the direct exploration of extraterrestrial bodies, and enter the most rewarding phase of lunar exploration. In the manned exploration of the moon we will reach the culmination of the lunar program.

Figure (8) The RANGER spacecraft under construction in the shops of the Jet Propulsion Laboratory in Pasadena, California.

Figure (9) 85-foot directional antenna in Goldstone, California, used for tracking the RANGER spacecraft.

Figure (10) Sketch of a design for the SURVEYOR spacecraft.

Figure (11) Possible structure for an unmanned mobile vehicle designed for navigation across the lunar surface.

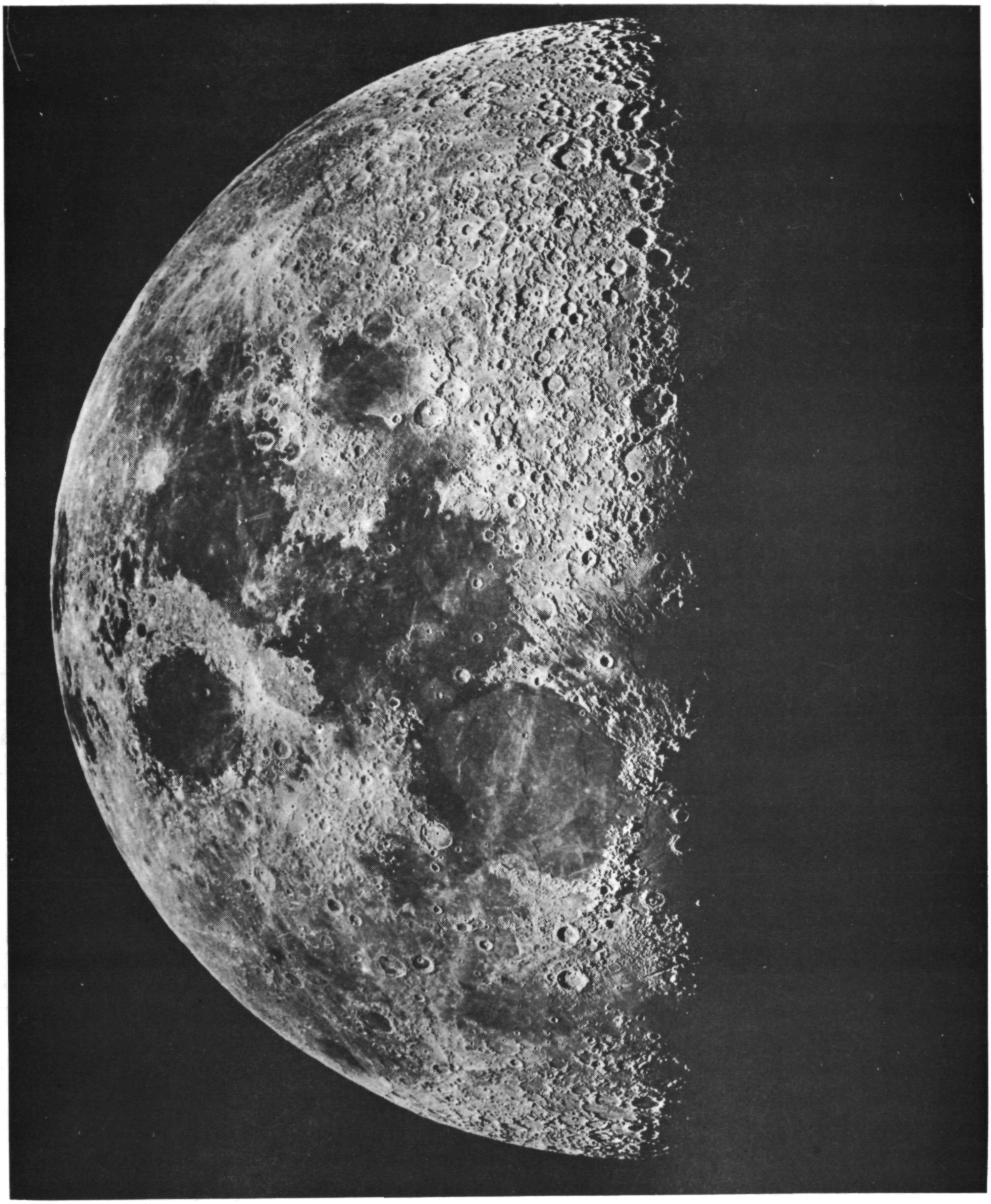

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Figure 1. Photograph of the moon showing circularity of the craters.

Figure 2. An artist's conception of the moon's surface, gathered from lunar photographs in which the long shadows exaggerated the relief of the surface features giving an erroneous impression of the terrain.

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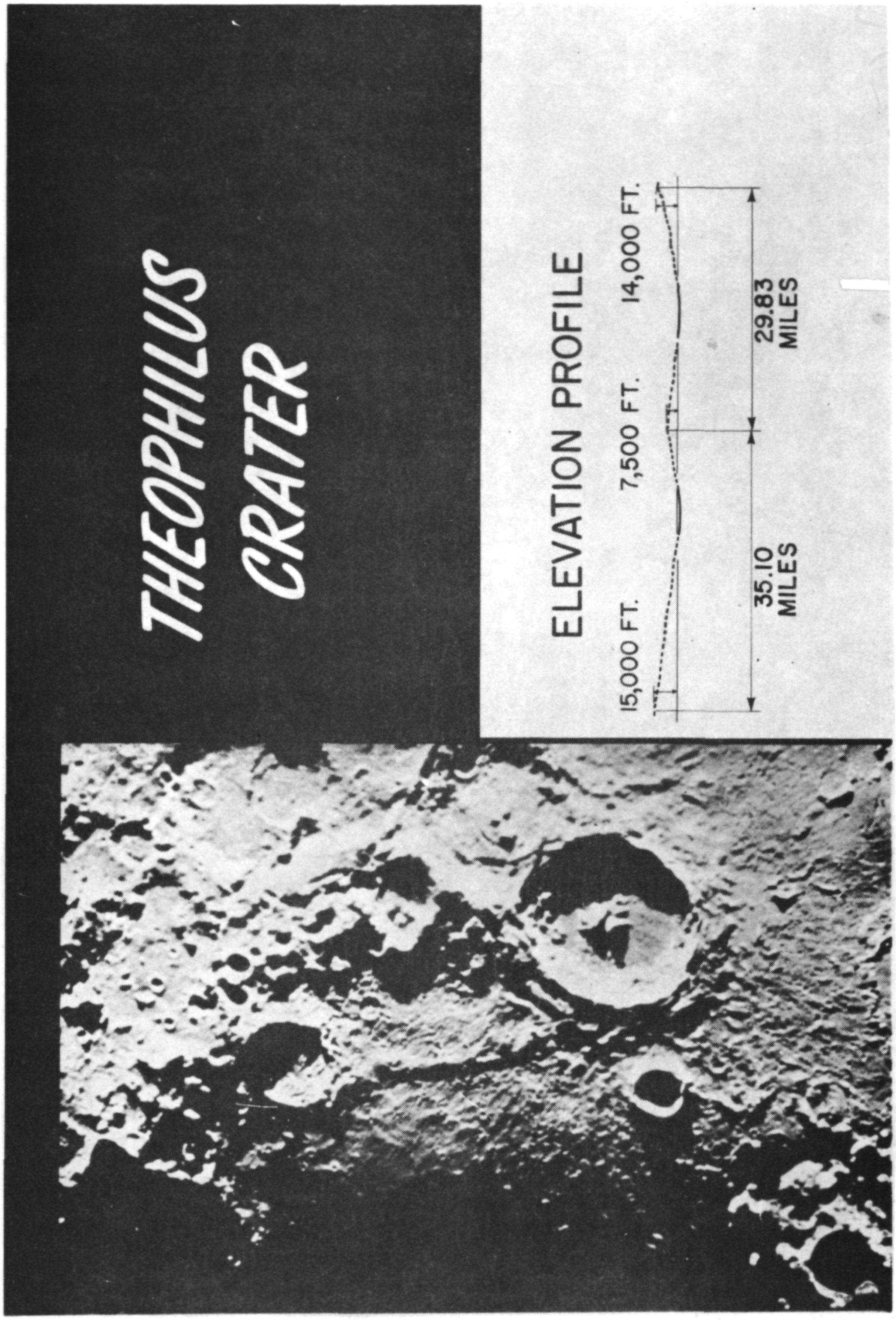

Figure 3. Photograph of Theophilus, a crater in the southwest sector of the moon. The elevation profile represents a cross-section through the center of the crater.

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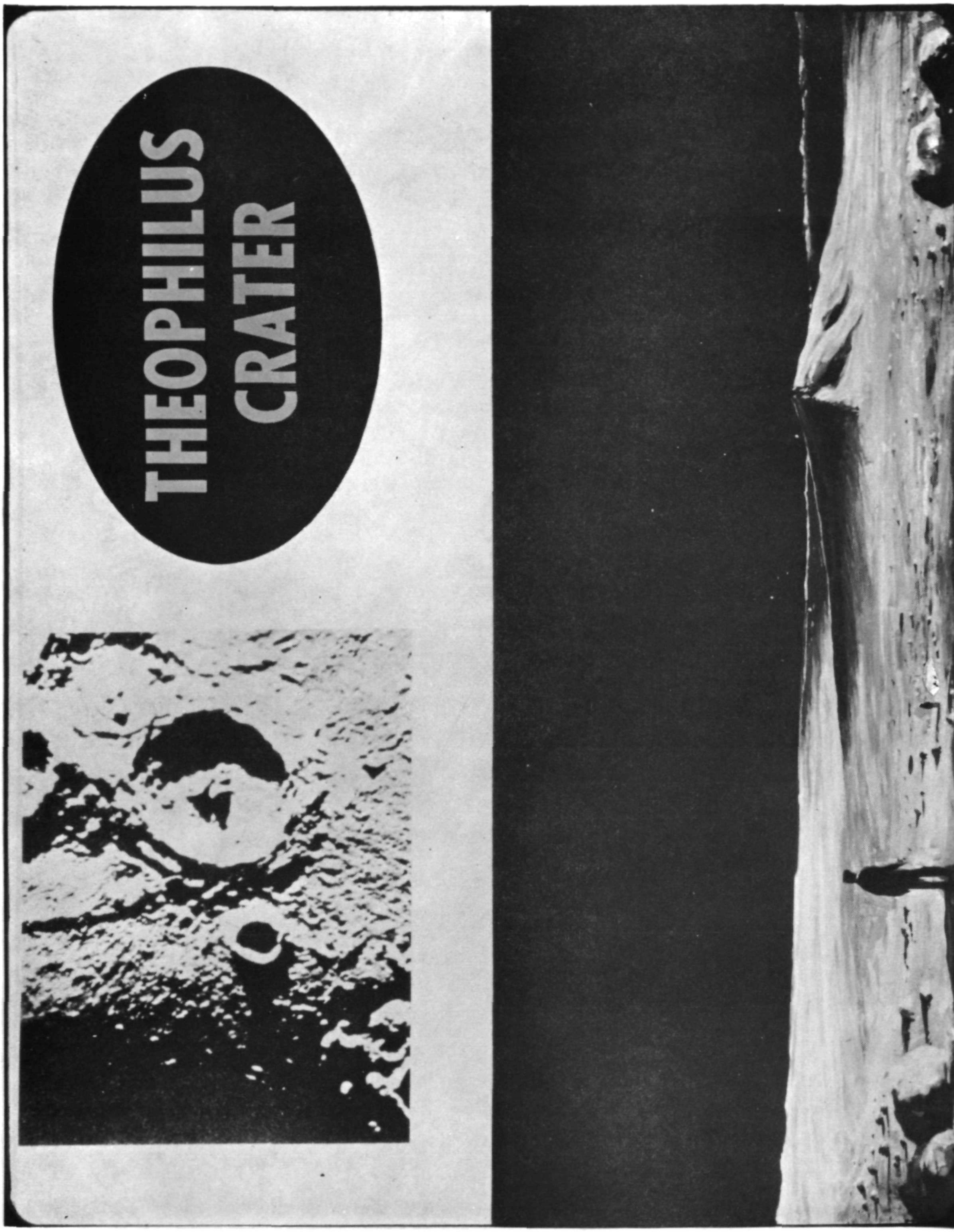

Figure 4. An artist's sketch of Theophilus, to accord with the elevation profile, compared with an actual photograph of the crater.

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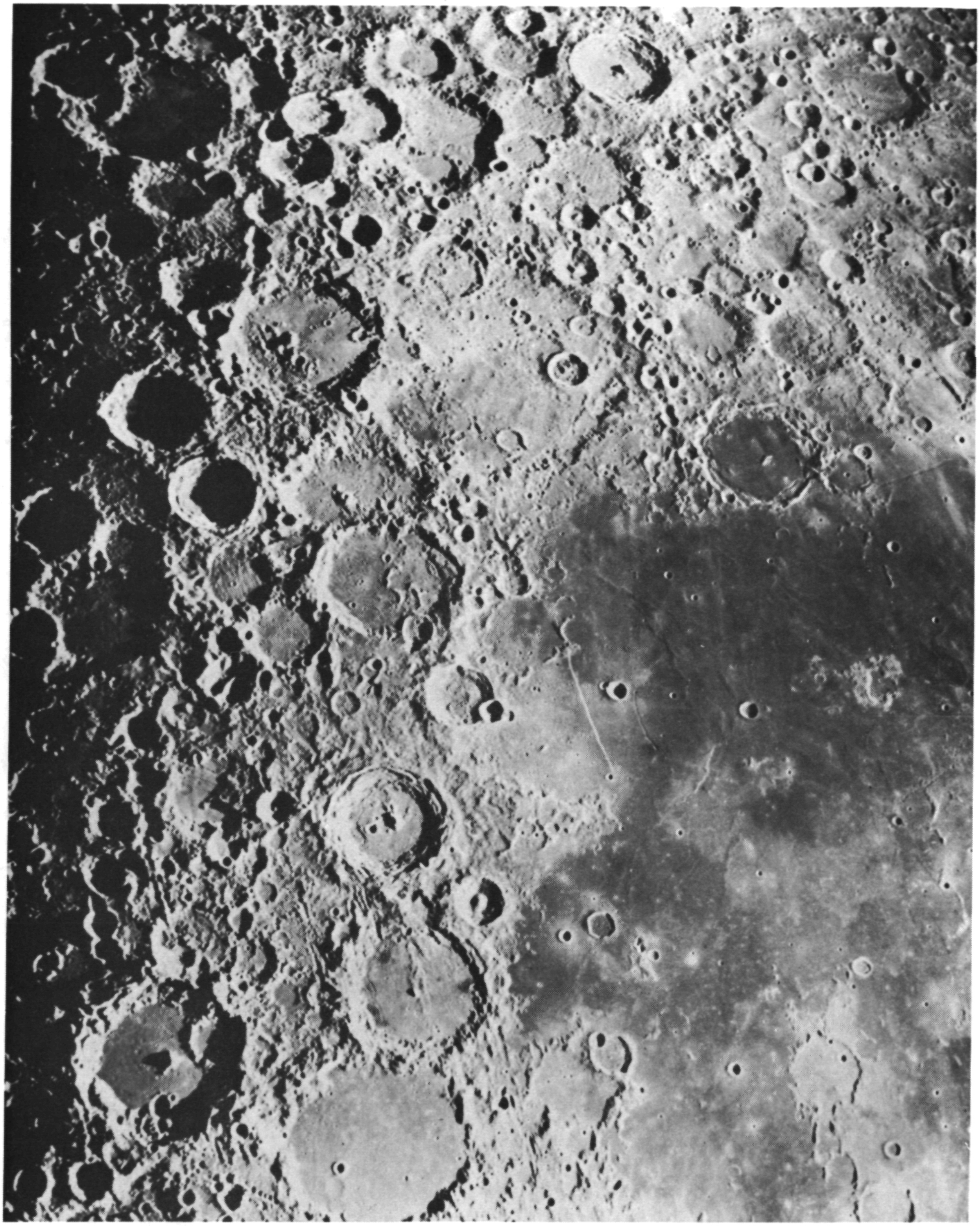

Figure 5. Mare Tranquilitatus in the western section of the moon.

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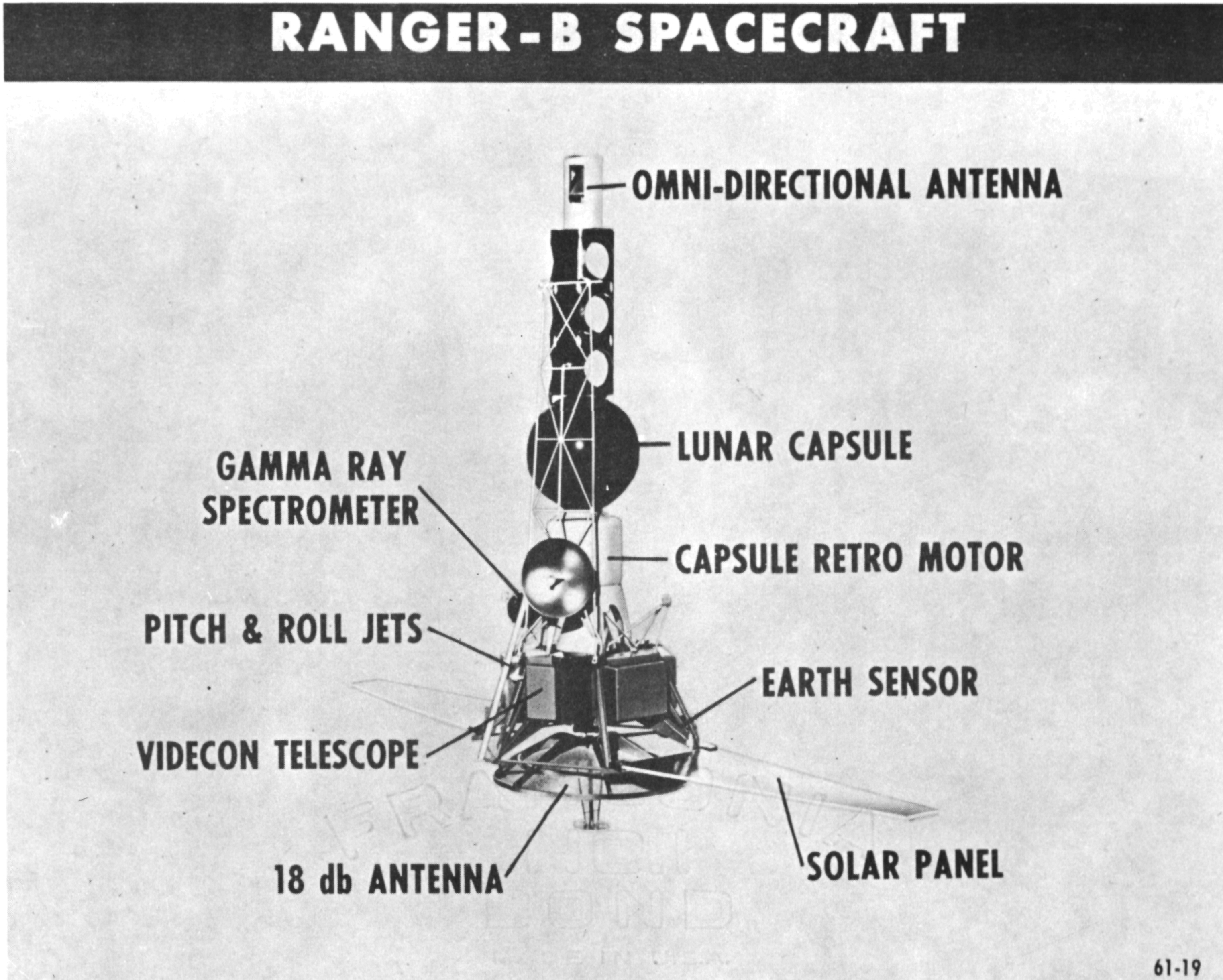

Figure 6. The RANGER spacecraft.

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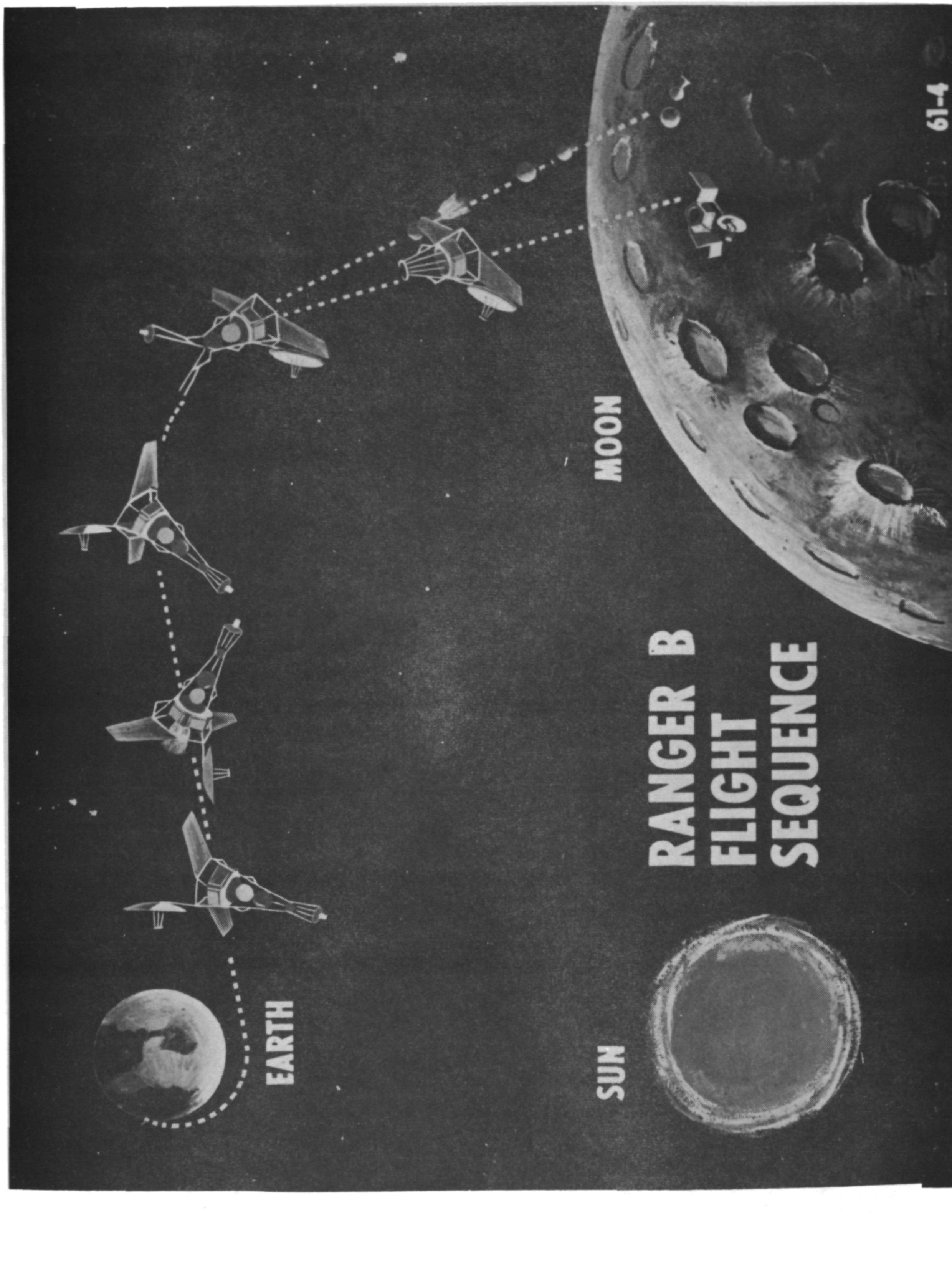

Figure 7. Sequence of actions planned during the approach of the RANGER to the surface of the moon.

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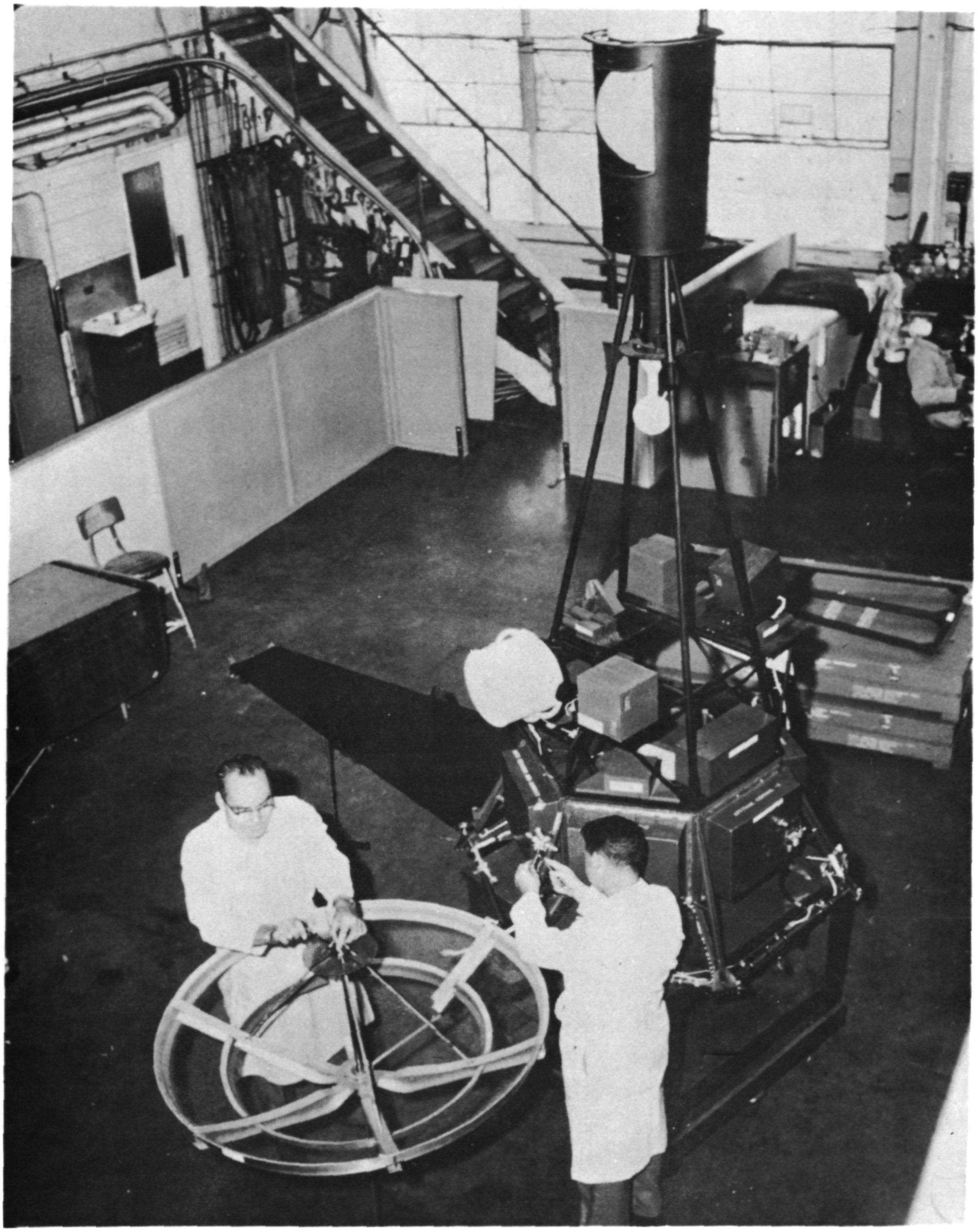

Figure 8. The RANGER spacecraft under construction in the shops of the Jet Propulsion Laboratory in Pasadena, California.

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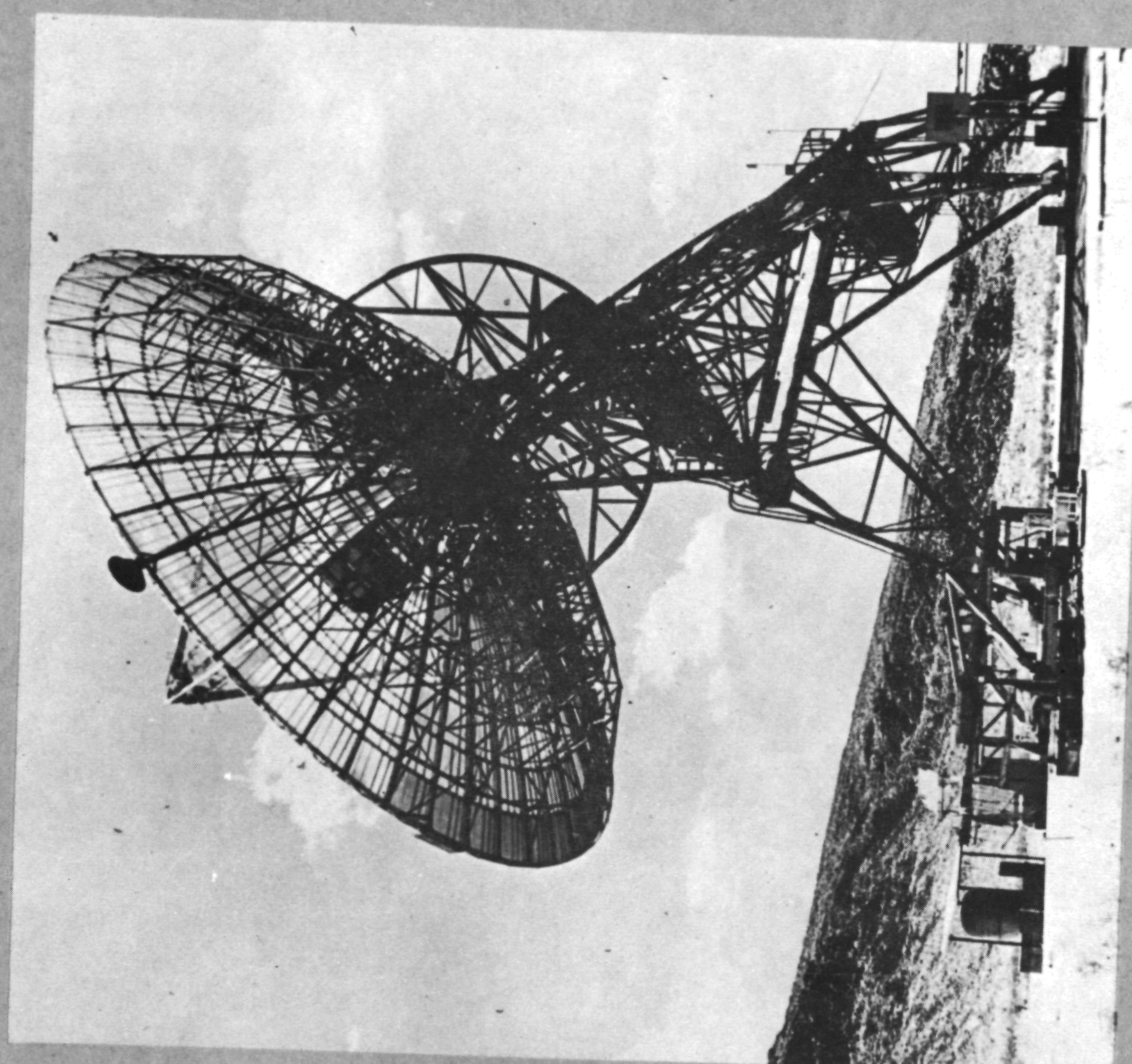

Figure 9. 85-foot directional antenna in Goldstone, California, used for tracking the RANGER spacecraft.

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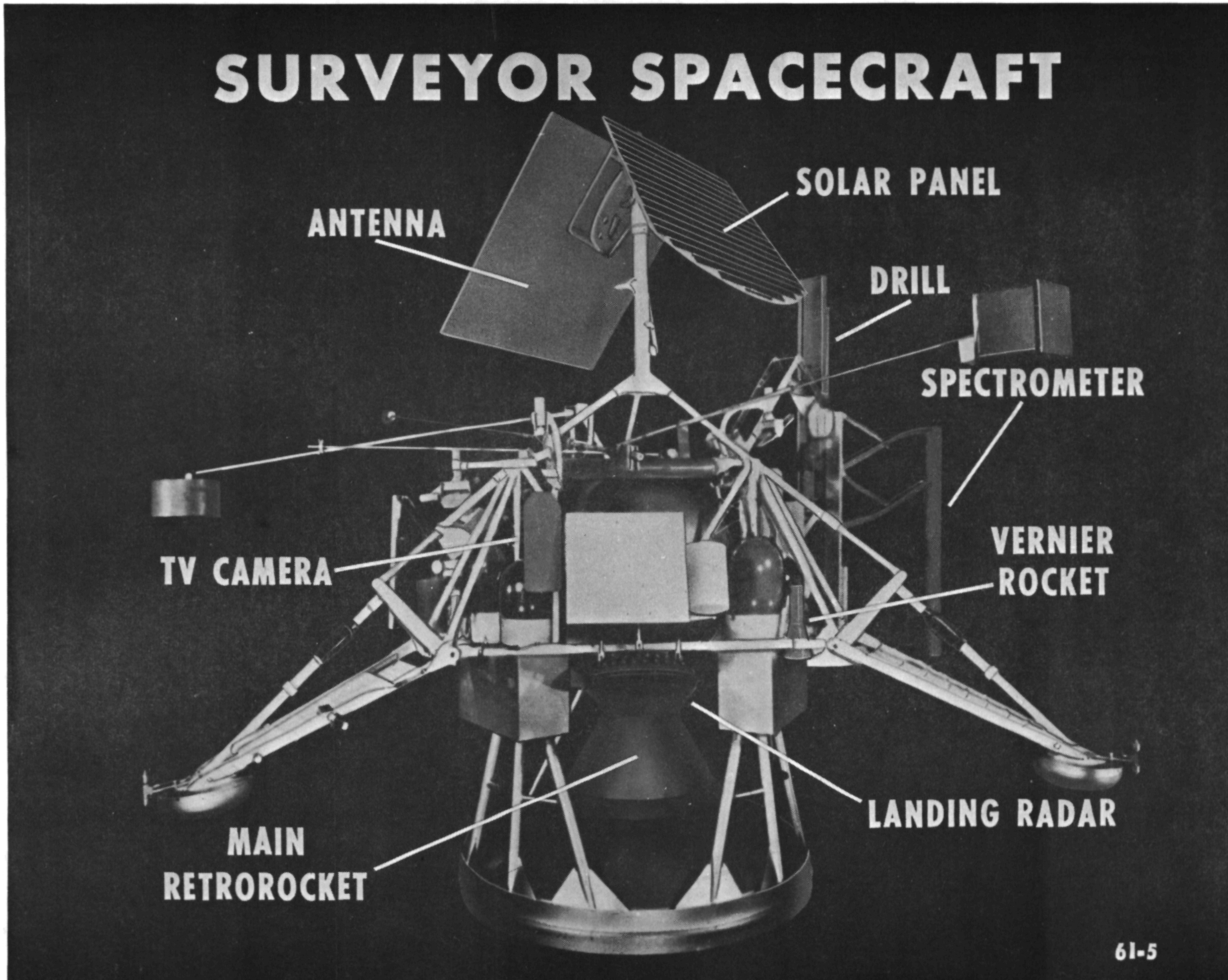

Figure 10. Sketch of a design for the SURVEYOR spacecraft.

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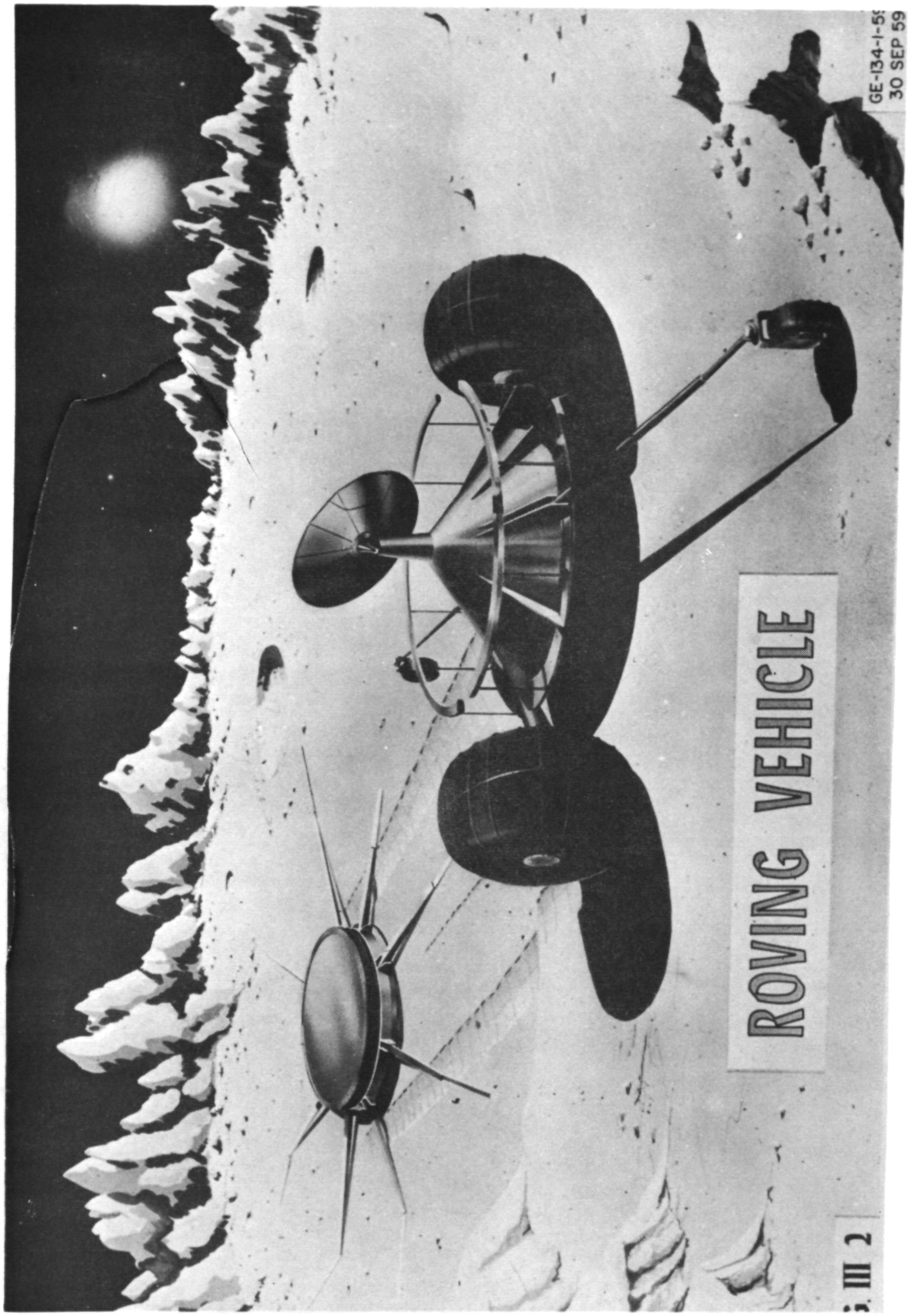

Figure 11. Possible structure for an unmanned mobile vehicle designed for navigation across the lunar surface.

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